Available online at www.sciencedirect.com

ScienceDirect

Physica E 40 (2008) 1273–1275

PHYSICA E

www.elsevier.com/locate/physe

Aharonov–Bohm oscillations in p-type GaAs quantum rings

Boris Grbić[a,*], Renaud Leturcq[a], Thomas Ihn[a], Klaus Ensslin[a,*], Dirk Reuter[b], Andreas D. Wieck[b]

[a]Solid State Physics Laboratory, ETH Zurich, 8093 Zurich, Switzerland
[b]Angewandte Festkörperphysik, Ruhr-Universität Bochum, 44780 Bochum, Germany

Abstract

We have explored phase coherent transport of holes in two p-type GaAs quantum rings with orbital radii 420 and 160 nm fabricated with AFM oxidation lithography. Highly visible Aharonov–Bohm (AB) oscillations are measured in both rings, with an amplitude of the oscillations exceeding 10% of the total resistance in the case of the ring with a radius of 160 nm. Beside the h/e oscillations, we resolve the contributions from higher harmonics of the AB oscillations. The observation of a local resistance minimum at $B = 0\,\mathrm{T}$ in both rings is a signature of the destructive interference of the holes' spins. We show that this minimum is related to the minimum in the $h/2e$ oscillations.

PACS: 73.23.−b; 71.70.Ej; 85.35.Ds; 03.65.Vf

Keywords: Aharonov–Bohm oscillations; Spin–orbit interactions; Spin interference; Quantum ring

---

The Aharonov–Bohm (AB) phase [1] represents the geometric phase acquired by the orbital wave function of the charged particle encircling a magnetic flux line. This phase is experimentally well established and manifests itself through oscillations in the resistance of mesoscopic rings as a function of an external magnetic field. The spin part of the particle's wave function can acquire an additional geometric phase in the systems with strong spin–orbit (SO) interactions [2,3]. The SO induced phase additionally modulates the resistance oscillations in mesoscopic rings. This SO induced phase in solid-state systems has been recently the subject of a number of experimental investigations [4–10].

SO interactions are particularly strong in p-type GaAs heterostructures, due to the p-like symmetry of the states at the top of the valence band and the high effective mass of holes. The presence of exceptionally strong SO interactions in carbon doped GaAs heterostructure used for fabrication of rings investigated in this work, is demonstrated by the simultaneous observation of the beating in Shubnikov–de Haas (SdH) oscillations and weak anti-localization in the measured magnetoresistance. The hole density in an unpatterned sample is $3.8 \times 10^{11}\,\mathrm{cm}^{-2}$ and the mobility is $200\,000\,\mathrm{cm}^2/\mathrm{V\,s}$ at a temperature of 60 mK. The strength of the Rashba SO interaction is estimated to be $\Delta_{\mathrm{SO}} \approx 0.8\,\mathrm{meV}$, while the Fermi energy in the system is $E_{\mathrm{F}} = 2.5\,\mathrm{meV}$.

Here we study AB oscillations in two quantum rings with radii 420 and 160 nm realized in this 2DHG with strong SO interactions. In contrast to previous experiments on p-type GaAs rings, where the signature of the phase acquired by the hole's spin was attributed to the splitting of the h/e peak in the Fourier spectrum [4,5], we have recently reported the direct observation of beating in the measured resistance of the quantum ring with an orbital radius of 420 nm [10]. An example of the observed beating in the gate configuration $V_{\mathrm{pg1}} = -172\,\mathrm{mV}$ and $V_{\mathrm{pg2}} = -188\,\mathrm{mV}$ of the large ring is shown in Fig. 1(a), while the corresponding splitting of the h/e Fourier peak is shown in Fig. 1(c). In addition, we observe a resistance minimum at $B = 0\,\mathrm{T}$ in all gate configurations, and attribute its origin to the destructive interference of the holes' spins propagating along time reversed paths [10].

We now focus on the magnetotransport measurements performed on the smaller ring with an orbital radius of

---

*Corresponding authors. Tel.: +41 44 633 3606; fax: +41 44 633 1146.
E-mail addresses: grbic@phys.ethz.ch (B. Grbić), ensslin@phys.ethz.ch (K. Ensslin).

1386-9477/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2007.08.129

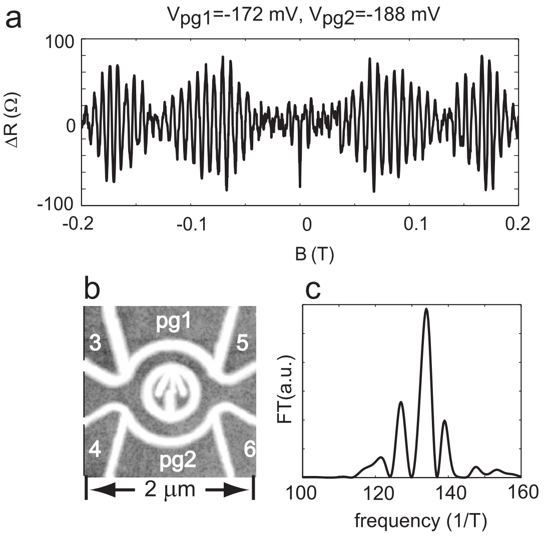

Fig. 1. (a) AB oscillations in the gate configuration $V_{\mathrm{pg1}} = -172\,\mathrm{mV}$ and $V_{\mathrm{pg2}} = -188\,\mathrm{mV}$ obtained after subtraction of the low-frequency background from the raw data. A clear beating pattern is revealed in the AB oscillations. (b) AFM micrograph of the large ring with an orbital radius of 420 nm with designations of the in-plane gates. (c) Splitting of the h/e Fourier peak.

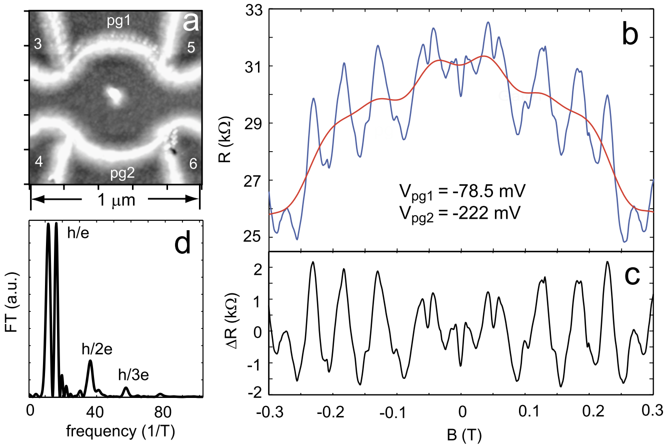

Fig. 2. (a) AFM micrograph of the small ring with an orbital radius of 160 nm with designation of the gates. (b) Measured magnetoresistance of the small ring (oscillating curve, blue online) together with the low-frequency background resistance (smooth curve, red online) in the plunger gate configuration $V_{\mathrm{pg1}} = -78.5\,\mathrm{mV}$, $V_{\mathrm{pg2}} = -222\,\mathrm{mV}$. (c) AB oscillations obtained after subtraction of the low-frequency background from the raw data. (d) Fourier transform of the data with split h/e peak and well defined $h/2e$ and $h/3e$ peaks.

160 nm (Fig. 2(a)). Fig. 2(b) shows the magnetoresistance of the small ring (oscillating curve, blue online), together with a low-frequency background resistance composed of the low-frequency Fourier components of the signal (smooth curve, red online) in the plunger gate configuration $V_{\mathrm{pg1}} = -78.5\,\mathrm{mV}$, $V_{\mathrm{pg2}} = -222\,\mathrm{mV}$. AB oscillations, obtained after subtraction of the low-frequency background from the raw data, with a peak-to-peak amplitude of $\sim 4\,\mathrm{k\Omega}$ are clearly resolved (Fig. 2(c)). Therefore, the visibility of the AB oscillations is larger than 10%. The

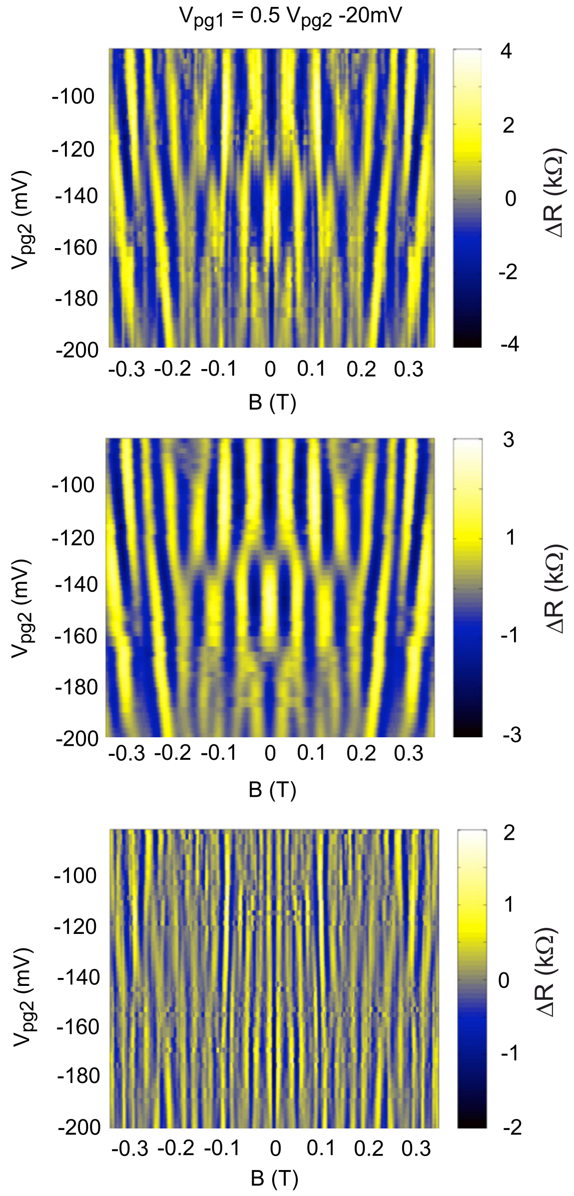

Fig. 3. (a) Evolution of the AB oscillations upon changing plunger gate voltages along the line $V_{\mathrm{pg1}} = 0.5 \cdot V_{\mathrm{pg2}} - 20\,\mathrm{mV}$ in parameter space. (b) Filtered h/e oscillations as a function of plunger gate voltages, showing phase jumps. (c) Filtered $h/2e$ oscillations as a function of plunger gate voltages, showing the minimum at $B = 0\,\mathrm{T}$ at all gate voltages.

Fourier transform of these oscillations reveals a split h/e peak, with side peaks at 12 and $17\,\mathrm{T}^{-1}$. Besides, $h/2e$ and $h/3e$ peaks are clearly visible (Fig. 2(d)). The electronic radius of the holes' orbit of 150 nm, obtained from the period of the oscillations of around 60 mT, agrees well with a lithographic mean radius of the holes' orbit.

Due to the large period of the AB oscillations, only up to 10 oscillations are present in the magnetic field range ($-0.3\,\mathrm{T}$, $+0.3\,\mathrm{T}$) where SdH oscillations do not obscure the data analysis and no beating can be seen in the raw data. Therefore, although the amplitude of the AB oscillations in the case of the small ring is quite large, a detailed analysis of the beating of the AB oscillations cannot be performed for this sample as it was done in the case of the larger ring [10].

We further analyze the dependence of the AB oscillations on plunger gates voltages. The evolution of the AB oscillations along the line $V_{\mathrm{pg1}} = 0.5 \cdot V_{\mathrm{pg2}} - 20\,\mathrm{mV}$ in parameter space $(V_{\mathrm{pg1}}, V_{\mathrm{pg2}})$ is investigated in Fig. 3. Fig. 3(a) shows the raw data, while Figs. 3(b) and (c) show filtered h/e and $h/2e$ oscillations, respectively. When V_{pg1} and V_{pg2} increase along the given line, both ring arms become narrower and the holes' orbit inside the ring shrinks, causing the resistance of the ring to increase continuously from 20 to 50 kΩ.

We again observe a resistance minimum at $B = 0\,\mathrm{T}$ in all gate configurations (Fig. 3(a)) and find that it is related to the minimum in the $h/2e$ oscillations at $B = 0\,\mathrm{T}$ (Fig. 3(c)), consistent with the results from the large ring sample [10,11]. It should be emphasized that the observed minimum is not caused by weak anti-localization in the ring leads, since the weak anti-localization dip in bulk two-dimensional samples has a much smaller magnitude (less than 1 Ω) than the minimum at $B = 0\,\mathrm{T}$ in the rings [11]. The resistance minimum at $B = 0\,\mathrm{T}$ is a result of the destructive interference of the holes' spins in the ring.

The presence of phase jumps in the h/e oscillations (Fig. 3(b)) and their absence in the $h/2e$ oscillations (Fig. 3(c)) are also observed. The fact that the phase of the AB oscillations cannot change continuously, but only in discrete steps of π is a consequence of the Onsager relations $G_{ij}(B) = G_{ji}(-B)$. For changes of the plunger gates along the line $V_{\mathrm{pg1}} = 0.5 \cdot V_{\mathrm{pg2}} - 20\,\mathrm{mV}$ we indeed observe phase jumps of π in h/e oscillations at lower magnetic fields up to 0.2 T, but at the higher fields, above 0.2 T, we find continuous monotonic shifts of the AB minima and maxima (Figs. 3(a) and (b)). We attribute these continuous shifts of the AB minima and maxima toward higher fields upon increasing plunger gate voltages V_{pg1} and V_{pg2} to an increase of the AB oscillation frequency upon continuous shrinking of the holes' orbit within the ring. Continuous, but non-monotonic top-gate induced shifts of the AB minima and maxima were recently observed in HgTe quantum rings [7], and this behavior is interpreted as a manifestation of the Aharonov–Casher phase.

In conclusion, we have measured highly visible Aharonov–Bohm oscillations in two quantum rings with radii 420 and 160 nm fabricated by AFM oxidation lithography on p-type GaAs heterostructure with strong SO interaction. The visibility of the AB oscillations exceeds 3% in the larger ring and 10% in the smaller ring. Beside the h/e oscillations, the higher harmonics of the AB oscillations are resolved in both rings. A resistance minimum at $B = 0\,\mathrm{T}$, present in both rings, points to the signature of destructive interference of the holes' spins propagating along time-reversed paths.

References

[1] Y. Aharonov, D. Bohm, Phys. Rev. 115 (1959) 485.
[2] H.A. Engel, D. Loss, Phys. Rev. B 62 (2000) 10238.
[3] A.G. Aronov, Y.B. Lyanda-Geller, Phys. Rev. Lett. 70 (1993) 343.
[4] A.F. Morpurgo, J.P. Heida, T.M. Klapwijk, B.J. van Wees, G. Borghs, Phys. Rev. Lett. 80 (1998) 1050.
[5] J.B. Yau, E.P. De Poortere, M. Shayegan, Phys. Rev. Lett. 88 (2002) 146801.
[6] M.J. Yang, C.H. Yang, Y.B. Lyanda-Geller, Europhys. Lett. 66 (2004) 826.
[7] M. König, et al., Phys. Rev. Lett. 96 (2006) 076804.
[8] T. Bergsten, T. Kobayashi, Y. Sekine, J. Nitta, Phys. Rev. Lett. 97 (2006) 196803.
[9] B. Habib, E. Tutuc, M. Shayegan, Appl. Phys. Lett. 90 (2007) 152104.
[10] B. Grbić, R. Leturcq, T. Ihn, K. Ensslin, D. Reuter, A.D. Wieck, Phys. Rev. Lett. in print.
[11] B. Grbić, Ph.D. Thesis No. 17248, ETH Zurich, 2007.